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REVIEW

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An annotated analytic review of biosynthetic polymers and circular business models in textile industry

Kende Kalman[1*], Tibor Alpár[1] and Arnold Tóth[2,3]

*Correspondence:
Kende Kalman
Kende.Kalman@phd.uni-sopron.hu
[1]University of Sopron, Sopron, Hungary
[2]Budapest University of Economics and Business HU, Budapset, Hungary
[3]Ludovika University of Public Service HU, Budapest, Hungary

Abstract

The increasing tendency to use synthetic polyesters in the textile industry since the 1990s has been transformed by alternating material use with bio-based forms, with environmental concerns supported by regulations and customer consciousness for more than a decade. Although some textile companies have developed their operations in favor of a circular business model (CBM), more progress still needs to be realized, specially in eco-design applications. Polyesters, with their specific material qualifications, provide textile companies opportunities to produce textile products for a variety of applications, specially for technical textile applications. For sure, this is not a random selection for both producers and customers, considering the material property and economic factors. In this research we have aimed to find the answers to the questions that whether biosynthetic polymers can fully replace fossil-based polymers in textile applications and what are the current challenges in establishing a fully circular business model in the textile industry. For this purpose we have realized our analysis based on polymer material analysis, ecodesign, recycling systems, business management and market behavior levels using cross literature review, descriptive review, as well as modelling methods for efficiency analysis methods. According to the findings, material development pacing local needs is expected to increase in the near future considering the regional economy and environmental conditions. Through more developed and scaled recycling solutions within closed-loop and open-loop systems, aggregated inert textiles can be significantly decreased. As long as the environmentally negative externalities are eliminated without missing the objective criteria of the material application, the green transformation can yield a positive response from textile customers. Behavior against price premiums may still remain a question until alternative products are launched; however, from a business and customer perspective, it will also be a factor in the buying decision stage. The environmental regulations and scale economy to be reached, depending on the demand for these new eco-textiles, are other determinants in the market.

Keywords Textile business, Polymers, Circular business models

JEL Classification M21, L65, L67, Q50

1 Introduction

1.1 Environmental aspects

As a substudy area of environmental economics, industrial ecology supports the idea of a separate eco-system for industries that coexist with the bioecological system [1]. On the other hand, ecological economics considers all the ecological systems within the bioecological system as a single model [2]. Here, the material science applications realized via the eco-design method can be key factors binding these two perspectives to each other. If considered in operation flow, apparel and other finished fabrics are made of textiles and textiles are produced via fibers, fibers on the otherhand can be formed via using different sources such as cotton, silk, wool and polymers. The more eco-designed products are developed, the more the industrial ecology converges into the bioecological system. Material sciences contribute to heterogeneous product range creation, and here, recyclable and sustainable applications are prioritized.

Biological materials science has been a rapidly growing branch of materials science and engineering, which has three distinct but interrelated components: (1) biological materials, i.e., natural materials; (2) biomaterials, i.e., synthetic materials in biomedical and textile applications; and (3) biomimetics, i.e., bioinspired materials and design [3].

The term biodegradable plastics refers to materials that keep their mechanical strength during practical use but breakdown into low-molecular-weight compounds and non-toxic byproducts after their use [4]. This breakdown process is realized through micro-organisms (such as bacteria, fungi, and algae) interacting with the material (such as a non-water-soluble polymer material) [5, 6]. Enzyme biotechnology may have the potential to improve the biodegradation of polymers [7]. These biodegradable plastic materials can be created through chemical synthesis, fermentation by microorganisms, and chemically modified natural products [8].

The textile industry is highly polluting, given the large volumes of energy and water required to produce clothing [9, 10].

It has been noted in the related literature that the decarbonization level in fashion industry can significantly be improved by elimination of both fossil fuel power supplies and the linear business model of fast fashion [9, 11]. Inconclusion, it is necessary for fast fashion brands to take precautions for reducing the negative perception occur against fast fashion in terms of sustainability [9]. Such precautions might include the use of recycled materials, reductions of CO_2 emissions, and conservation of water and natural energy resources [9, 12].

Compared with the environmental consequences of biomass cultivation used for producing bioplastic and biofuel, the balance may occur when biomass resources are used for PE manufacturing rather than for biofuel production [13, 14] by considering the lower GHG emission advantages of hybrid vehicles compared with battery electrical vehicles [15], specially in regions where the carbon intensity of electricity matrix is high.

1.1.1 Material comparison of conventional plastics and bioplastics

Poly(ethylene terephthalate) (PET), poly(trimethylene terephthalate) (PTT) and poly(butylene terephthalate) (PBT) are well known and are the most studied polymers belonging to the poly(alkylene terephthalate) (PAT) family, but many other polymers in this family whose full potential has not yet been disclosed [16]. The overview of applications in which PATs are used includes sectors such as electronics, automotive, textiles, packaging, medical and others [16].

Polyethylene terephthalate (PET, PETE, or the obsolete PETP or PET-P) is the most common thermoplastic polymer resin of the polyester family and is used in; fiber production for clothing, containers for liquids and foods, thermoforming for manufacturing, and in combination with glass fiber for engineering resins [16].

Polysaccharide-based polymers are made of fruit and vegetable originated elements, such as cellulose, starch, chitin/chitosan, pectin, alginate, and carrageenan which are counted among one the most promising biopolymer-yielding fibers in polysaccharide family [17]. Among other vegetable-based biopolymers as a source of fiber there are soy, whey, and zein which are protein-based unlike polysaccharide-based polymers [17].

Polymer degradation refers to; chemical, physical, or biochemical reaction resulting in a change in its chemical properties and a reduction in its molecular weight [18]. This process can be realized in two ways: via biodegradation, which can be realized through soil (composting), freshwater or sea water, either naturally or via a planned specific experimental disposal system [19]. Alternatively, synthetic methods may also be compatible with the bioenvironment [18].

Biodegradable plastics made from bio-based polymers are becoming increasingly important for replacing the massive amounts of conventional nonbiodegradable fossil-based plastics that have been produced and disposed of in recent decades [20].

Polman et al. [20] indicate that knowledge about degradation process of unmodified biopolymer can be used to predict the biodegradation specifications of their corresponding modified biopolymer type to a considerable extent. Specially in TPS, where only during the bioplastic-making process a greater level of structural change occurs, the biodegradation mechanisms and rates are virtually similar [20].

Specific additives are also required in production of bioplastics similar to the conventional plastics to overcome the basic property limits for using these materials in diverse applications [18, 21]. However these additives can potentially cause toxicity risk for terrestrial and aquatic ecosystems due to their migration from the plastic or due to their nondegradable feature [18]. Therefore it is extremely important to assess the biodegradibility conditions of each bioplastic type by considering their residual specifications and the disposal system [18]. So in the circular economy (CE), considering these products as an input of industrial ecologic system after their primary use is reasonable.

There might be a trade-off between textile quality and the environmental effects of the material, which can be considered an important target subject of improvement. What is yet to be further considered is whether bio-based textiles are fully secure for current technical textile applications, such as industrial clothing applications for workers. In which areas are bio-based textile materials applicable?

1.2 Business aspects

Designers of eco-fashion products for instance prefer using natural fibers or recycled materials or both in differing extent [22]. Even some conscious consumers' perception of eco-textiles are queite similar to those of fabrics that are made from cotton, silk or wool [22]. Cotton as the largest natural fiber in the global market scale represents approximately 77% of all natural fibers (including manmade cellulosics) produced in the world

[22, 23]. The Natural fiber production industry generates significant amount of revenue and job in global scale [22].

However, it is important to note that growing of regular cotton plants require large amounts of land, high quantities of pesticides and fertilizers, and high water consumption [22, 24] moreover, some ethical issues exist regarding its genetically modified types [22].

Agriculture chemicals applied in significant amount as a consequences of conventional (regular) cotton production processes, cause; environmental detoriation and health issues for human, as well as decrease in effectiveness of pesticides and higher costs of production [25]. According to the World Economic Forum and BCG report, fashion industry's significant amount of carbon emission comprised by scope3 type emissions tracing back to raw material producers such as cotton growers [26, 27]. Production of synthetic polyester materials requires fossil fuel consumption and production of conventional cotton requires very high amount of water usage, therefore the composite materials consisting of synthetic polyester and conventional cotton (PET-CO blend fabrics) are unsustainable [28], Using organic cotton [28] and some renevable polyesters [29–31] specially in apprel industry can provide environmentally a far better solution. Regular wool production process has also negative environmental consequences, and cause doubtful animal welfare practices (mulesing Merino sheep) [22]. Results of fiber production Life Cycle Assessments particularly about environmental impacts revealed that there are many alterantive fibers on the market, which could be used for eco-fashion, rather than the conventionals (regular ones) [22]. Fibers based on renewable raw materials which follow eco-friendly production processes should not be ignored by designers of eco-fashion, considering life cycle assements [22] which is also an important assesment for environmental accounting.

According to the parameters published in 2025 by the textile exchange organization concerning global fiber production in 2024, there are approximately 132 million tons of fiber production, among which 69% consists of synthetic fibers (Fig. 1). Approximately 85% of the total synthetic fibers are composed of polyester (Fig. 2).

Considering the heterogenic product range, and market demand, the use of polyester as a material provides qualifications (color tones, tissue, surface, and anti-flamability in industrial applications) that enable designers to create a variety of products with lower costs, which can be called flexibility and economic advantages of this material. On the

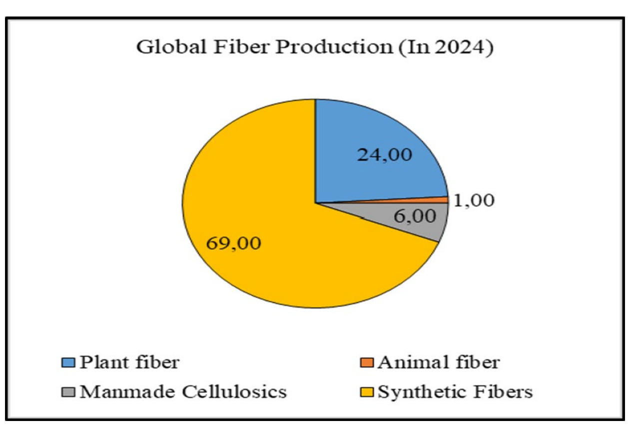

Fig. 1 *Source* Textile exchange organization

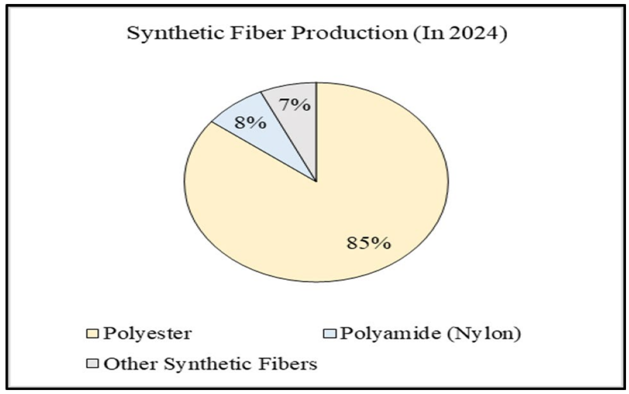

Fig. 2 *Source* Textile exchange organization

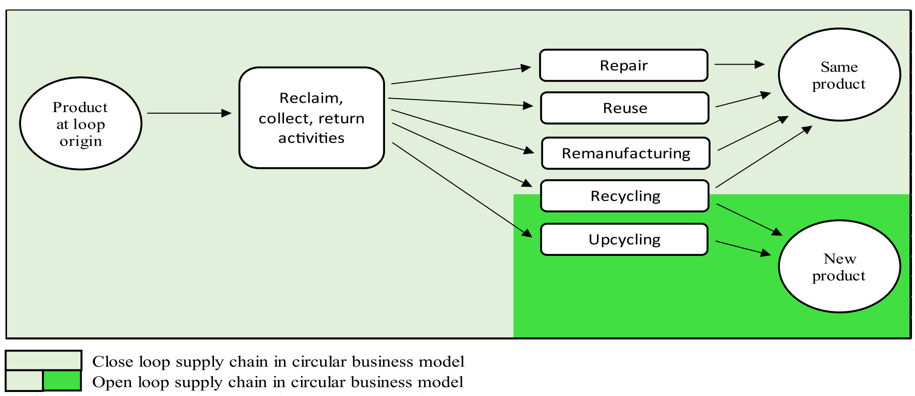

Fig. 3 Close and open loop supply chains (Resource: [33])

other hand, the environmental factors of polyesters are a limit, with the best scenario being the industrial ecologic steady state. Therefore, biodegradable solutions substituting polyethylene (raw material of polyester) would improve the environmental consequences of textile products. There are textile producers who have already declared their sustainability policies accordingly with the use of a biotextile input strategy. The material to be chosen as input for production is one of the subjects at the center of the circular business model of many new and existing textile companies.

For reaching more viable economic conditions and for reducing negative environmental impacts, making integrated plans for the product lifecycle and value creation architectures within circular business model approach including each successive cycles of, repairing, reusing, remanufacturing and closing material loops is pivotal [32]. A close loop supply chain (CLSC) can respond to this need, and this supply chain can be integrated into different stages of the product life, as well as into other primary and secondary products [33]. This means that an upcycling generating a new higher value product within an open loop supply chain can be also transformed to a closed loop in it's own business operations cycle [33]. A close loop and open loop supply chain is visualized in Fig. 3.

In their researches Nussholz [32] and Bocken and Ritala [34] concentrated on integrating circular economy principles into the business model elements (business model canvas) developed by [35] and value dimensions conceptualized by Richardson [36]. Nussholz developing a mapping tool for circular business model based on case study.

Bocken and Ritala conceptualize circular business model strategy frame work in an 2× 3 matrix consisting of 2 innovation strategy and 3 resource strategy where innovation strategy is determined based on *open* (being connected with external parties) and *closed* (acting within the firm boundaries) cases, and resource strategy determined based on *narrowing loops* (focusing on efficiencies in design and production processes), *slowing loops* (refering to extend the product life time for longer period of utilization) and *closing loops* (refering to recycling processes).

Material studies are closely related to eco-design product development [17] and incorporated to business development [37] and circular business models [38]. In this research, both the prominent raw material of textiles as polymers and environmental factors have been reviewed within the scope of the circular business model approach. Polymers with their dynamic structure, enabling them to become textiles in different composite forms, provide textile producers a wide range of textile types available for use in various applications. There are already promising methods and technologies developed for the future [17]. Textile business operations have the potential to converge increasingly more into circular business models in open and/or closed loop forms in the future.

2 Methodology

Because this is an interdisciplinary subject of research, consisting of two main study fields, material science and business studies, the research review content has been structured as an annotated analytic review of polymer qualifications and their place in the textile industry and the industry's current challenges in transition to circular business models. For this purpose, the literature has been used to evaluate polymer types and their behaviors against biodegradation, and environmental concerns and solutions, such as a circular business model, have been discussed from the perspectives of ecodesign, recycling systems, business management and market behavior. Cross literature review, descriptive review, as well as modelling methods for efficiency analysis are applied to enlight the answers of the following questions; (1) Can biosynthetic polymers fully replace fossil-based polymers in textile applications? and (2) What are the current challenges in establishing a fully circular business model in the textile industry?. Literature resources are selected based on their subject content of polymer specifications, the polymers used in textile products, and these materils economics & environmental impacts in scope of circular economy and circular business models. literature about environmental economics and bioeconomy, management sciences and market reports have been also used as a review research. Considering overall content, this research is an annotated analytic review of polymers as a material and their place in textile industry within the scope of circular business model transformation processes.

3 Reducing the negative environmental impact of polyesters for textiles

There are two main options for reducing the environmental impact of polyester in the textile industry. One solution is replacing fossil-based production raw materials with those of biological origin, and the second is replacing polyester with biodegradable polymers. The replacement of petrochemicals with chemicals by transforming carbohydrates, which constitute 75% of biomass annually, is a significant challenge for green chemistry. Moreover, some bio-based polymers are not biodegradable materials although they are renewable. The polymers might be categorized as shown in Fig. 4.

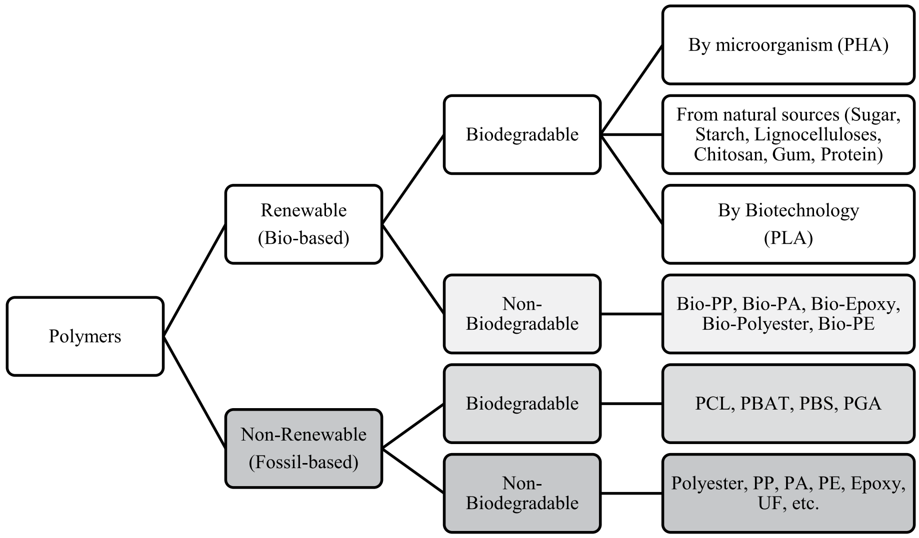

Fig. 4 Categorization of polymers on the basis of origin and biodegradability (based on [29–31]) PHA, Polyhydroxylalkonates; PLA, Polylactic acid; PP, Polypropylene; PE, Polyethylene; PCL, Polycaprolactone; PBAT, Aromatic copolyesters; PBS, Aliphatic copolyesters; PGA, Polyesteramids; PA, Polyamide; UF, Urea formaldehyde

3.1 Bio-based polymers

Patti and Acierno [31] overview the future scope of biopolymers for sustainable use in textile utilization. Plant- and animal-derived polysaccharides encompass compounds such as starch, cellulose, and lignin. Proteins, including chitosan and collagen, serve as key biopolymeric materials. Lipids, such as waxes and fatty acids, contribute to biopolymer composition. Microbial activity facilitates the synthesis of biopolymers like polyhydroxyalkanoates (PHA). Bio-based monomers include polylactides (PLA) and polyglycolides (PLG). Synthetic bio-monomers comprise polycaprolactones (PCL), polyester-amides (PEA), and various aliphatic or aromatic co-polyesters, such as poly(butylene succinate-co-adipate) (PBSA) and poly(butylene adipate-co-terephthalate) (PBAT).

Zhang et al. [39] summarized the origin and production of bio-based polyesters made of aliphatic and aromatic monomers. They also describe bio-based polyester elastomers such as thermoplastic polyester elastomers (TPEEs) and thermosetting polyester elastomers. As the report lists the aliphatic polyesters can be originated from diacids and diols, binary copolyesters, hydroxy acids, lactones, polyfunctional monomers, and terpenoid-derived monomers. Bio-based aromatic polyesters can be terephthalate, furan dicarboxylic acid, or vanillin-based polyesters. A further category is bio-based polyester elastomers. This includes bio-based thermoplastic polyester elastomers and bio-based thermosetting polyester elastomers.

Wang et al. [40], Suzuki et al. [19] and Zhao et al. [41] collected bio-based polyesters derived from renewable resources. The studies mention Polyhydroxybutyrate (PHB), Poly(3-hydroxybutyrate-*co*–3-hydroxyvalerate) PHBV, polylactic acid (PLA), poly(e-caprolactone) (PCL), Polybutylene succinate (PBS), Polybutylene adipate terephthalate (PBAT), Polyglycolide (PGA), Polyvinyl acetate PVA. A detailed list summarized by Wang et al. including the data of;, melting point, glass transition temperature, tensile strength, elastic modulus [MPa], elongation at break [%], production cost [€/ton] and biodegradability features of these materials are stated in Table 1.

Table 1 Comparison of material features/polymer type mechanical properties, crystalinityn degradability, processing properties, and cost of commercial biodegradable resins with non-degradable resins *source* Wang et al. [40]

Polymer	Tg [°C]	Tm [°C]	Tensil strength [mpa]	Elastic modulus [mpa]	Elongatiat break [%]	Market share [%]	Production cost [€/ton]	Biodegradability
LDPE	−100	98–115	8–20	300–500	100–1000		1150	−
Starch						38.4	400	+
PHB	5–10	177–182	40	700–1800	6–8	2.2	3800–6400	+
PHBV	0–30	100–150	10–40	600–1000	10–500			+
PLA	40–70	130–180	44–65	2800–3500	10–240	25	2200–2600	+
PCL	−60	59–65	4–28	390–470	700–1000	< 25	3000	+
PBS	−32	114	40–60	500	170–500	7.7	2000	+
PBAT	−30	110–115	25–40	65–90	500–800	24.1	1500	+
PGA	30–40	225–230	89	7000–8400	30	< 2.5		+
PVA	58–85	150–230	28–65	30–530	50–230			+

−Technically possible but it takes hundred of years besides the negative environmental externalities

+Depending on; the soil, sea or fresh water environment, the material dimentions and the climate conditions, biodegradable in changing ratios

Poly(lactic acid) is a bio-based thermoplastic polymer synthesized from lactic acid obtained through the fermentation of naturally occurring polysaccharides. It is both biodegradable and compostable, and exhibits comparatively favorable structural properties relative to other biodegradable bio-based plastics [42]. While PLA demonstrates potential for applications in medicine, textiles, and packaging, its inherent brittleness, low softening temperature, and poor water vapor and gas barrier properties limit its broader utilization [42]. To expand its application range, enhancements in barrier, thermal, and mechanical performance are essential. Studies indicate that the incorporation of a small amount (1 wt%) of ultrasonically treated cellulose in PEG 400 significantly reduces PLA brittleness and yields a tougher material [42]. Nevertheless, further investigation is required to improve the interfacial compatibility between cellulose and PLA. Cellulose-derived micro- and nanomaterials show considerable promise in this regard [42]. Moreover, research by Stloukal et al. [43] demonstrated that the addition of anti-hydrolysis agents enables the development of diverse PLA-based materials, offering pathways to tailor biodegradability or enhance resistance to degradation.

The study of Ivanovič et al. [44] conducted a comparative Life Cycle Assessment (LCA) of fossil-based polyester (derived from PET) and its bio-based alternatives, including bio-polyester (drop-in), PTT fiber (smart drop-in), and PLA fiber (novel), all produced via melt spinning. Currently, these bio-based replacements rely on primary feedstocks such as corn and sugarcane, with significant production overlaps between bio- and fossil-based PET and PTT, allowing the modification of existing production infrastructure.

The effect evaluation revealed that only three of the nine bio-based alternatives performed within the range of conventional polyester. The environmental benefits of bio-polyester and PTT were largely influenced by the bio-PTA component, highlighting the need for more precise modeling. Climate impact results varied significantly depending on carbon crediting, with reductions of reaching 70% when considering biogenic carbon in the analysis. However, without circular economy principles, such reductions may be misleading.

Additionally, bio-based fibers exhibited increased eutrophication, acidification, ecotoxicity, and land/water use impacts, correlating with their bio-content. Fossil fuel dependence remained only slightly reduced. To address these concerns, three key strategies are proposed: exploring alternative bio-fibers, shifting to second-generation feedstocks, or improving agricultural practices.

For environmentally sustainable textile manufacturing, future fabric development should prioritize biodegradability. Renewable resource-derived alternatives such as bio-PET and bio-PA, which possess fiber characteristics similar to conventional synthetics, offer a promising path forward. However, their non-biodegradability could exacerbate existing environmental issues related to fossil-based filaments, particularly in disposal. Despite this, durable bioplastics can match petroleum-based counterparts in performance while integrating into existing recycling streams. Moreover, their production significantly reduces greenhouse gas (GHG) emissions. Life-cycle assessments comparing bio-PE and PLA to fossil-derived HDPE and LDPE (generally used in packaging applications) demonstrated lower GHG emissions and lower fossil fuel consumption for bio-based alternatives.

While biogenic carbon uptake presents environmental benefits, end-of-life considerations remain critical. PLA, for instance, shows increased emissions when disposed of in landfills rather than composted due to methane emissions. In summary, while bio-based textiles offer potential sustainability advantages, they require further optimization, particularly in biodegradability, end-of-life management, and the transition to second-generation feedstocks, before they can be considered viable green alternatives. [44–47]

Polymer degradation refers to the breakdown of polymeric materials due to chemical, physical, or biological processes, leading to structural and property changes over time. Another categorization is photodegradation (by UV light), thermo-oxidative degradation (by heat—burning) and biodegradation. Among various degradation pathways, biodegradation is of particular interest due to its environmental implications. Biodegradation occurs when microorganisms eg. bacteria and fungi enzymatically break down polymers into smaller molecules, ultimately converting them into carbon dioxide (CO_2), methane (CH_4), water (H_2O), and biomass under aerobic or anaerobic conditions [48].

Biodegradation typically occurs in several stages: *Enzymatic hydrolysis*—enzymes secreted by microorganisms cleave polymer chains into smaller oligomers or monomers. *Microbial assimilation*—these microbial cells subsequently take up the smaller fragments, which are further metabolized. *Mineralization*—during the final stage of biodegradation, complex metabolic pathways lead to the formation of new products, with CO_2 and H_2O generated during aerobic degradation, the anaerobic process on the otherhand results in the generation of both $CO_2$and CH_4 in contrast, to aerobic processes [18, 49, 50]

Biodegradation represents a viable disposal route for readily hydrolyzable polymers, including aliphatic esters such as polylactic acid (PLA), cellulose-based materials, and starch films, unlike more crystalized and hydropobic types such as polyethylene furanoate (PEF) [18, 51]. Environmental conditions: temperature, humidity, oxygen availability, and microbial population density impact degradation rates [52, 53].Molecular weight and structure: lower molecular weight and amorphous regions degrade faster than highly crystalline or crosslinked structures. Biodegradability of biodegradable in comparing with non bio degradible polymers are shown in Table 1.

We can distinguish between biologically sourced and fossil-based polymers. A major advantage of biologically sourced polymers is that they are produced from renewable raw materials and are part of a nature-based carbon cycle. During their degradation, they release the same carbon (CO_2) back into the environment that they absorbed from the atmosphere through photosynthesis during their formation.

Biologically sourced polymers that are not biodegradable are less favorable, as they originate from renewable sources but can only be disposed of through incineration. However, their key advantage over fossil-based polymers is that they also release only the carbon (CO_2) they initially absorbed from the atmosphere through photosynthesis.

In contrast, fossil-based polymers—whether biodegradable or not—emit carbon (CO_2) into the environment during degradation or incineration that had been stored in the Earth's outer shell for millions of years. As a result, they are not part of the natural carbon cycle.

From a sustainability perspective, a ranking can be established: the most favorable polymers are those that are both biologically sourced and biodegradable. Second in line are biologically sourced but non-biodegradable polymers. They are followed by fossil-based biodegradable polymers, while the least favorable are fossil-based polymers that are not biodegradable. Polymers as a material input, specially particular types, takes significant amount in textile industry (Figs. 1 and 2) and these facts improve the importance of polymer analysis for the economic and environmental measures to take place in circular business model strategies. In next subsection the polymer material qualification, production economy and environmental consequences are evaluted via efficiency perspective.

3.2 An efficiency model approach

In textile industry since polymer based material takes significant portion as input, analysis of the process in material durability, production economy and environmental consequences together would be reasonable conduct in business operations. In this section an efficiency analysis is applied considering these three factors together for a comprehensive look to the textile business case.

Biodegradable polymers are known for their nonlinear and time-dependent mechanical behavior, as recorded by the experimental results [54].

To evaluate the service efficiency, the mechanical parameters of the materials, their production conditions and the environmental consequences of these activities should be considered together.

Considering the following: the QSAR-based biodegradability model of Okey and Stensel [55],the kinetic models of Liu et al. [56] and Ding&Wang [57], decolorization analysis of polyester fabric realized by Fei et al. [58],Tests realized by Masuelli [59] via Mark–Houwink parameters for aqueous-soluble polymers and biopolymers at various temperatures; durability analysis of biodegradable polymer nanocomposites realized by Glaskova et al. [60] and constitutive modeling of biodegradable polymers realized by Vieira et al. [54] and in addition to the changing target and conditions of the experiments, with respect to the material life cycle against degrading and fatigue agents as a function of duration, the molecular weight analysis has been in the center of the durability measurement which is formulated as following;

$$\eta = k * M^{a} \tag{1}$$

where M is the molecular weight, η is the intrinsic viscosity, and k and a are material-specific technical parameters that vary with temperature, polymers and solvents [59]. Masuelli [59] calculated the Mark–Houwink parameters via an iterative method for aqueous-soluble polymers and biopolymers (PVA-co-VAc, gelatin B, pectin, and xanthan gum) at various temperatures with the following equation *"ln* $[\eta] = ln\ k + a^{*} ln\ M_w$" and the Mark–Houwink parameters "a" and "k" were successfully calculated to determine the molecular weight.

On the basis of the analysis of PLA-PCL during hydrolytic degradation (h_d) in a phosphate buffer medium at 37 °C for 16 weeks, the findings revealed the following relationship:

$$h_d = 1 - \sigma_t/\sigma_0 = 1 - M_{nt}/M_{n0} = 1 - e^{-u*t} \tag{2}$$

where σ_t and M_{nt} are the strength and the number-average molecular weight of the polymer at degradation time t; σ_0 and M_{n0} are the corresponding initial (nondegraded) strength and molecular weight values, respectively; u is the degradation rate of the polymer; and t is the duration [54, 60, 61]. By incorporating this relation into constitutive models such as the Neo-Hookean and Mooney–Rivlin hyperelastic models and the

Bergström–Boyce viscoelastic model for polymers that undergo significant deformation, the stress–strain behavior of PLA-PCL fibers was effectively predicted for different degradation times [54, 61]. The approach could be validated for the other biodegradable polymer types [60]. Explaining the relationship via the Young modulus of elasticity at time t (E_t) = σ/ε, where ε represents tensile strain, $\sigma_t/\sigma_0 = E_t/E_0 = e^{-\lambda t}$ [60] if viscous (strain (ε)-dependent) parameters are assumed to be unaffected during degradation.

If Eq. (2) is reregulated,

$$1 - \mathrm{h_d} = \sigma_t/\sigma_0 = \mathrm{M_{nt}}/\mathrm{M_{n0}} = e^{-u*t} \tag{3}$$

The molecular weight at time t can be expressed as follows [54, 60, 62]

$$\mathrm{M}_{nt} = \mathrm{M}_{n0} * e^{-u*t} \tag{4}$$

and when

$$\mathrm{M}_{n0} = \mathrm{M} \tag{5}$$

For the naturalized $\mathrm{M_{nt}}$;

$$\mathrm{M}_{nt} = \left[(\eta/k)^{1/a}\right] * \left[e^{-u*t}\right] \tag{6}$$

where a and k are temperature-dependent values and are also expressed exponentially [59]

Referring back to Eq. (3), if durability (D) as a basic service factor (S) of a textile is simply represented with strength and molecular weight as follows:

$$\mathrm{D} = e^{-u*t} \tag{7}$$

Considering circular business model operations such as production and recycling, the cost factor can be defined as follows:

$$\mathrm{C} = \text{cost factor} = \text{production costs} + \text{degradation costs}$$

$$\begin{aligned} &\text{Production cost monetary value of fibre} + \text{degradation cost of fibre} \\ &\quad = \left[\mathrm{v_p} + \mathrm{f_p}/\left(\mathrm{q_p} * \mathrm{u_p}\right)\right] + \left[\mathrm{v_d} + \mathrm{f_d}/\left(\mathrm{q_d} * \mathrm{u_d}\right)\right] \end{aligned} \tag{8}$$

where v is the unit variable cost, f is the total fixed cost, q is the capacity, u is the capacity usage ratio, p represents production, and d represents degradation. The cost calculations can be realized through raw material, labor, and machinery hours and energy consumption plus fixed costs, which can be measured with monetary value.

$$\mathrm{E} = \text{Net Environmental Factor} = \text{Negative Externalities} - \text{Positive Externalities}$$

Negative Externalities (N) = Monetary value of emissions and other residual material fees per quantity of treadmill material.

Positive Externalities (P) = Monetary value of all positive externalities per quantity of material, which can be deductable from the monetary value of negative externalities per quantity of treadmill material.

$$\mathrm{E} = (\mathrm{N} - \mathrm{P}) \tag{9}$$

Here, if the company eliminates the negative externality by its own effort without paying an environmental fee corresponding to this negative externality, this value is considered a negative externality (unless otherwise, it is stipulated in terms of environmental regulation).

Via the ultimate efficiency model approach of Daly [63], efficiency can be expressed as follows:

$$\text{Environmental Efficiency Ratio} = \text{S/E} \tag{10}$$

$$\text{Economic Efficiency Ratio} = \text{S/C} \tag{11}$$

$$\text{Total (Factor) Efficiency Ratio} = \text{S/(E + C)}$$

$$\text{Total (Factor) Efficiency Ratio} = e^{-u*t}/[v_p + f_p/\left(q_p * u_p\right) + (v_d + f_d/(q_d * u_d) + (N - P)] \tag{12}$$

The calculations for comparative analysis of degradation, durability, production cost and environmental externalities are performed via the same amount of materials under the same conditions of production, such as knitting methods. As a novel method of efficiency measurement, the model aims to provide an analytic perspective to the subject matter of the circular business model in the textile business.

In a randomly selected biodegrading process case, the trend of the degrading stages could not be parameterized as modeled here because, in this model, degrading should be realized in a controlled experimental environment. In a homogenized and controlled bioenvironment, the comparison level of the model between polymer types would increase and better approximate the measured values under these conditions.

With the approach of considering both material science, environmental accounting and production cost, the explained model aims to provide a comprehensive perspective to perform a precise evaluation of service efficiency. Although the model is useful for prospective analysis, the analysis results reached at a point in time can be improved later via the developed material features and their production process productivity with technology and demand. The prominence of material research and economic factors for developing the eco-design products in the industry is significant.

4 Business operations in the textile sector and circular business model (CBM)

According to the textile exchange organization report of 2025, the polyester fiber appliance portion in global scale approximately are as follows; apparel: 30–60%, home textiles: 20–35% and the remaining portion of polyester fibers are used for various other applications. Polyamide fibers are used in various applications, among those; there are apparel, home textiles such as carpets, as well as technical and industrial applications [23]. According to the analysis, the plastic footprint in the European Union, which is based on scientific literature and consumption statistics, among the total plastic in the postconsumption stage, the PP and PET types of polymers are among the most common materials included in textile products [64].

According to the EMI survey results, 42% of the companies among the 326 surveyed textile companies adopted a green technology or adopted a new green business model [65, 66].

The textile industry has been one of the distinct industries which utilizes recyclable material but also emited some harmful residuals [67–69]. Significant amount of textile and clothing (T&C) companies in the past focused more on to optimization of a linear clothing economy rather than establishing a fully circular business model [69, 70]. Although they utilized speed, trendiness, and cheapness, quality and sustainability were not the factors prioritized in this linear system [69, 70]. This has not caused higher volume of clothing production recorded ever before [69, 71] but also the accumulation of material in the postconsumption stage, carbon emission, and environmental pollution [68, 69].

The prominance of synergy between the society, environment and economy has been seen [14], but only in the last few decades has the issue of sustainability started to be considered in larger extent and systematically led researchers concentrating on the circular economy concept [72]. While organizations have made serious efforts to reach sustainability standards [69, 73, 74], the features of a circular economic system have not yet been fully understood in industry [69]. Circular economies (CE) that focus on protecting natural resources, maximizing outputs, and eliminating negative externalities, such as carbon emission and the accumulation of materials in the postconsumption stage [69, 71], are considered among the most promising solution to maintain the maximum value of the material during its use while eliminating toxic items through the close loop operation cycles [69, 75]. Therefore, from a social dimension perspective, a CE is an economic model in which whole operation cycle is designed and managed, to maximize ecosystem functionality and human well-being [76]. CE is anticipated to become one of the emerging subject to be prioritized by the companies in business modelling [77].

With new environmental governance and more environmentally conscious consumers, textile companies have started to seek better alternatives for their existing linear business approach [69]. All these progress are followed by emerging of CBM concept. A circular business model (CBM) is mainly defined as a product-service system aiming to transform the input to product via solutions that provides maximum utilization with using as more natural content as possible [69, 78] while focusing on how companies can propose, create, and capture value within a CE concept [69, 79]. Therefore, a CBM can be structured on the basis of products, services, or a combination of the two [69]. With respect to the circular business model, operations can be evaluated in two main stages from a material perspective: 1) developing eco-designs and 2) setting recycling systems.

The results of the research performed by Sandberg and Hultberg [80] demonstrate the importance of scaling in circular business models to maintain more sustainable business practices. This research was conducted via interviews with Swedish fashion companies and formed on the basis of integrating three dynamic capability dimension: sensing, seizing and reconfiguring, and three scaling dimension; scaling out, scaling up and scaling deep, as a 3 × 3 matrix provides a practical approach for utilizing dynamic capabilities via identifying (sensing), understanding (seizing), and organizing (reconfiguring) required for different scaling level of CBMs [80]. It is concluded by this research that, One of the most important microfoundations of scaling out are creating efficient routines and operations within the CBM, scaling up revolve around networking, and finally scaling deep involve the ability of influencing norms and cultures among clients and employees to create a succesful transformation in the market [80].

Considering the value dimensions Richardson [36], busines model canvas Osterwalder and Pigneur [35] and potential circular economy measures in a circular business model framework is visualized in Fig. 5.

Value Dimensions	Potential Circular Economy Measures
Value Proposition The product idea and the offering Determining the target customer Developing the basic strategy	**Product Design** Eco designing of products Considering objective material criterias Developing strategy with CE perspective
Value Creation Gethering all resources and managing capabilities Systemizing the indoor product/service generation Setting supply chains	**Green Supply Chains** Concentrating on green energy resources Improving recycling facilities Seeking green suppliers
Value Delivery Determining performance obligations Systemizing the product/service delivery After sales operations	**Delivery Efficiency** Optimizing logistics operations Using digital platforms Setting material collection systems after sales
Value Capture Calculation of costs and cash flows out Recognition of revenues and cash flows in Sharing the value	**Social Responsibility** Considering environmental consequences beside the financial facts Planning reinvestment ahead based on CE principles Sharing sustainability and financial information

Fig. 5 Circular business model framework

In this section the circular business concept will be evaluated in eco design, recycling systems, management approach and market behavior perspectives in the scope of polymers qualifications and textile industry conditions to reach a comprehensive resolution in this frame.

4.1 Eco designs

Eco design is one of the most prominent subject of circular business models [38, 69]. In addition to circular systems within industrial ecology, renewable eco-design products are essential for growing populations and economies. This however can be challenging, because the existing products might have a complex structure owing to objective quality criteria and may not carry complete circularity features, may aim the attention of only certain customer groups, or frequently may require redesign Guldmann and Huulgaard [81], [69]. Huang and Li [82] in their research synthesized insights from dynamic capabilities and social network theory, an the results revealed that dynamic capabilities, coordination capabilities, and social reciprocity are one of the most important innovation drivers of green product and green process which consequently improve organizational and environmental conditions. This transition process is relatively more challenging for technical textile development because of the more complex application-specific technical requirements expected from them.

While the resource-based view (RBV) is highly operation and firm-centric, an extended version of the RBV, natural RBV (NRBV), importantly involve also the influence of company resources on environmental conditions. [83–85].

According to the results of the research performed by Andersén [83], via analyzing the data of small-scale manufacturers operating in Sweden, in which the relationship among; green product innovation (GPI), product differentiation, relational resource to be provided by green suppliers and firm performance are examined;

- GPI affects the advantage of product differentiation, and this relationship is strengthened by the use of inputs provided by green suppliers.

- This research offers a relational natural resource-based view (RNRBV) of product innovation. By providing important products and complementary resources for the focal firm, the green suppliers can support these firms to fully utilize their own GPI capability.

In addition to scale and standardization, the technical textile segment is relatively more R&D focused owing to its' technical application requirements [86]. For example, depending on technical textile applications in diverse fields, such as for construction, medical and automotive applications, a superhydrophobic qualification in textile is necessary to reach the required liquid repellence and self-cleaning levels, as well as to form barrier coatings on fiber surfaces [87]. The adhesion between the treated fiber and the polymeric matrix has an important function in determining the interfacial strength of composites [88]. The surface adjustment of textile fibers by cold plasma is operationally simple, highly efficient, saves energy and cost, retains the intrinsic properties of the fiber, and is environmentally friendly [88, 89], although it is less repeatable due to technical limitations [89]. Syncronization of the production processes is not less important than solely chosen methods; the research by Kalazić et al. [90] conducted by using both novel and adapted methods about the influence of alkaline hydrolysis and chitosan coating on the roughness of polyester woven fabric, shows that optimization of textile finishing and washing processes are critical for reaching the required roughness levels.

According to the research results of Fuentes et al. [17], nanotechnology-based intelligent textile functionalities potentially to be seen in the future.

- Apart from their biodegradability advantage, without reinforcement of the material, the bio-based textiles do not present the required technical properties for many specific applications, in terms of durability (for example; resistance against tearing and abrasion), which is one of the most prioritized quality feature of a textile, and the applications of nanocoating can improve these features [17].

- Emerging companies have been concentrated on biotechnological R&D fields for scaling their production processes, and once the scaling targets are accomplished, these technologies will be able to be globalized to an increasing extent to expand the range of products that can be developed [17].

- Biotechnological advances in the development of new biofiber or biotextiles represent an attractive business [17]. In the near future, more sophisticated products can be developed to improve the functionality of textiles, which consequently contribute to human life and environmental protection [91].

4.2 Recycling systems

It is clear that the establishment of a recycling system with a circular business model approach for textile companies will be a reasonable way to maintain operations in the industry. The advantage of using renewable material resources such as bio-based polymers is the ability to utilize both closed-loop and open-loop recycling systems applied in CBM. In the case of an aggregate stock of polymers, the bio-based types can be recycled in an open-loop cycle (intersectoral) system, such as via an industrial symbiosis solution [92–96], within a cooperation model.

According to the research results of Baloyi et al. [97] concerning textile recycling technologies,

- Mechanical recycling method is suitable for 100% wool fibers, however it lowers the quality of fabrics made of blended fibers such as polycottons which cannot be easily separated in to their pure natural and synthetic contents via mechanical recycling methods.

- Chemical and biological recycling methods, on the other hand, provide recycling solutions for blended fabrics while protecting the fiber quality, although the processes of these methods have not been scaled in expected level. Current pretreatments are expensive, and the technology should be improved to become more sustainable and economically viable.

- The biological recycling technology used for textile fabrics are suitable for open-loop recycling systems (intersectoral), where renewable feedstock are used as input, whereas chemical recycling is a promising method for closed-loop recycling (textile to textile) of cellulosic textiles in the postconsumption stage, since this method does not cause a significant deteriorating effect on the unique qualifications of fibers during the recycling operations.

- A proved and effective method for recycling polyester fibers is degradation to TPA, which can be repolymerized for producing new polyester fibers.

Evaluating the current situation of the circular business model via the technoeconomic dimension [98] in the textile industry from eco-design and recycling perspectives, it can be stated that there are technologies that are already theoretically and experimentally demonstrated themselves although they are in the scaling stage of improvement.

4.3 Management approach

According to the research analysis results of business environment characteristic (BEC) realized by Chi [99] via 202 companies, dynamism was statistically found as the most prominent environmental characteristic among the four researched environmental characteristics (diversity, complexity, dynamism and competition) in the US technical textile industry.

Transformation of a linear business model to a circular business model when considering environmental factors may present some difficulties, specially for incumbent organizations. Overall, the path dependency which constrains the transformation capability of companies [100] potentially explains why many incumbent textile companies with a history of noncircular base production habits are still at the beginning of the journey towards CE [69]. The path dependency approach claims that the future direction of a company is directly influenced by its past decisions and actions [69, 101–103]

To explore which capabilities are critical to find solution for the inertia that create a barrier to the process of transformation from linear business models to circular ones, dynamic capability theory, which is centered upon the alignment of resources and capabilities for adapting organization to the changing business environment [104, 105] can be one of the first management theory approaches to consider in corresponding business research analysis [69].

While a business model (BM) outlines and also articulates a firm's operation flow towards value creation, value capture/appropriation and value delivery/share [106], business model innovation (BMI) can be described as a significant positive change in the principal elements of a company's business model and/or a reconfiguration in the architecture set of these elements contributing to productivity [107, 108]. From the perspective of the "*innovation ecosystem" (*IE), which is defined as an evolving set of actors, activities, artifacts, institutions and relations that are incorporated to and critical for the innovative performance of an actor or a group of actors [109], IEs present complexities that must be managed strategically through dedicated microfoundations of dynamic capabilities (MofDC) to achieve IE-based corporate social responsibility (CSR) targets [110]. As contingency theory suggests that there is not only a single optimal strategy eligible for all firms [111, 112]. Subject-specific exertise and strategy development are required because succesfull results can potentially be achieved via different methods depending on current conditions surrounding each firm having different business models [107, 113–115].

Evaluating the industry from a cooperation perspective, geographical clustering of textile firms for individual business and local industrial development; although the value chain of the textile industry has globalized, and operations of many textile firms comprise complex flow of activities realized through a worldwide business network [116, 117], this globalization has not diminished the vital role of geographical clustering of textile activities [117–121]. Clusters are defined as geographic concentrations and regional ecosystems comprising interconnected companies, specialized suppliers and companies operating in particular fields that "compete but also cooperate" (coopetition) [117, 122, 123]. This clusters also host associated institutions such as universities, standard-setting bodies, trade and industry associations [117, 122]. The European Cluster Collaboration Platform (ECCP) [124] is a prominent example of a cluster organization, where recently organized networking activities of polymer recycling (POLREC), cooperative trade fair of tools and processing industry (including polymer processing) (INNOFORM), platforms for knowledge exchange, research, and innovation in the fiber industry (where programs are also organized about biopolymers) (Dornbirn GFC) are some of the activities realized under the scope of the cooperation cluster of textile firms. Technology and product developing firms' operations rely on unique set of assets, capabilities and strategic routins [106, 125] as well as endowments associated with the cluster [117], which in turn increase the capability of the companies within this cooperation network. Routines and capabilities of the firms operating in the territory [126] are embedded to the shared network system and form the cluster resources via which potential of creating superior innovative capabilities are increased within this industrial cooperation network, where firms easily access to these shared resources [117], and find opportunity to improve their business and local industry as a whole.

4.4 Market behavior

The idea of ecological modernization is that the modern society has a capability that can be carried out through institutional reflexivity to build a capacity that enables society to handle a country's/regional ecological crisis [127]. Sustainability is structured on the basis of economic, social, and environmental measures, and when all these three criteria are met ideally in balance, sustainable development is possible [14]. Company and individual behaviors subject to these three criteria in the market have direct influence on the circular economy. Developing an effective recycling system requires individuals and companies to change their behavior to protect the environment [128]. The textile recycling operation as a process realized in postconsumption stage is also a significant part of the CE, considering the polymer-based textile content. Moreover, behaviors prior to recycling operations, such as purchasing and using habits (including consideration of the textile usage guide), tracing back to sources also significantly influence the environment. Hence, environmental consequences are influenced by both the before, during and postconsumption habits of textile customers and textile companies as a whole.

The results of the survey about apparel product purchase habits, as a preconsumption habit, realized via 19,000 consumers across 8 countries show that 71% of the consumers say that they are concerned about sustainability when purchasing apparel products, 38% adopt sustainable behaviors, and 12% act by purchasing sustainable products; however, only 3% pay premiums for more sustainable services [66]. There seems to be increased awareness of sustainability, however, there seems also to be a mismatch between the attitudes, behaviors and perceptions of customers [27, 66, 129]. Quality perceptions, objective norms, subjective tastes and/or prices as financial measurements of textiles might be factors that influence the decisions of customers to various extents at the total or group level or at the individual level. The importance of customer expectation fulfillment is also emphasized by Rese et al. [130] as a success factor in sustainable textile product innovation.

According to the study by Friedrich [131], where façade construction experts were surveyed to test their willingness-to-pay (WTP) and attitude toward façades parts manufactured via bioplastic-based textiles compared with petrochemical variants on the basis of planned behavior theory along with the experimental comparison analysis of bioplastic-based textile-and petrochemical-based textile material properties; although the majority of the surveyed building experts are open to considering such products, its main functional features are rated as inferior to those of conventional petroplastics [69]. Product information, which objectively improves credibility, is more likely to result in acceptance [131]. Therefore, the objective norms are more influential on buying decision than the deciders' personal attitudes do [131].

According to the results of the research of Friedrich [131],

- There is a favorable demand for bioplastics over synthetic materials in textile building applications by experts on the market. Suppliers should respond to this demand.

- Construction specialists seem not opposed to pay a price premium for bioplastics in construction products, particularly for the textiles used in building envelopes. The additional costs versus price premiums should be considered by the material developers when the biopolymer type is selected for development.

- Evaluating by objective performance criteria, the material features of bioplastic-based textile products for the building envelope application were comparatively inferior than the textiles made of petrochemical-based plastics. The developers should specially prove and guarantee technical requirements such as fungal resistance, toughness, and expected usefullife of the textile.

- The objective criteria of material properties strongly influence the willingness to buy and apply bioplastics, specially fire resistance criteria, which are also regulated by building laws for façades.

- The willingness to buy is more influenced by the operational and sectoral environment of the decision-makers, however personal consent already exists today to the product for the objectively secured applications potentially expected in the future.

These results indicate that there is a material property barrier in the sales of bio-based textile applications in the construction sector, although there is a positive attitude and potential demand for these bio-based products.

Another study was conducted by Salmi and Kaipia [69], via an empirical case study to reveal the mechanisms that enable companies to shift CBM. Answers for two questions have been researched; How do past trajectories influence the position of clothing companies in the move toward CBMs? Which capabilities are critical to overcome transformation-related challenges? [69]. The 7 companies for case analysis were selected among Finnish clothing brands to represent both incumbent organizations with a long history in linear economy and younger, born-circular startups that were founded at the very beginig on CE principles [69]. The results revealed that the product focus and dependency on the existent product portfolio influence the method of companies' business model transformation process [69]. Companies need to develop their sensing and seizing capabilities to go beyond the linear business culture and to restructure their resources accordingly [69]. The position in the global value chain influences the method through which companies can adopt circularity [69]. A strong position, which enables companies to control the circularity of the value chain, can be achieved through ownership and control over the supply chain, production resources and the actual product, or through allying in business ecosystems and networks [69].

According to the results of the research of Salmi and Kaipia [69],

- The born circulars, need specific capabilities for supplier and ecosystem management to ensure circularity principles in the whole supply chain. In addition, for a wider customer portfolio and to develop the market, circular-born companies need to provide customer incentives to receive attention of new customers in the market.

- The linear incumbents on the other hand were tightly stuck in their current product portfolio, but in various forms due to different reasons. While one company aimed durabilty in its' products which draw high reuse interest, another was aiming the high comfort and elasticity standards which provide less options of recyclable materials substitutable with the existing ones. In general, leaving from a linear business model was found to require a remarkable change to make in their business culture.

Polyester dependency of the sector can be a factor behind the consequence of existing product portfolios being produced relatively in linear incumbents (instead of in an entire circular business model) because, as a material, polyester in various composite forms provides durability, comfort and elasticity as well as a budget advantage, which makes sense for consumers. Of course, material research on biopolymers can provide solutions for substituting synthetic materials. Overall, client behaviors are another key determinant of this consumption.

5 Conclusion

This research contributes to the literature by providing an annotated analytic review of the textile sector via resolution in the material and business dimensions, where one of the most prominent raw materials of textiles, biosynthetic polymers, and their role in the circular business model are discussed considering also market perspective.

In textile industry specially in apparel segment both function and appearance carry greate importance, which often results in the demand of textiles having complex structure [72]. Improving the original structure of the material and adding new functions can be achieved via material, mechanical, and/or chemical functionalization [72]. In terms of efficiency, considering both environmental effects, cost and service quality balance on the basis of a complete circular business model can be considered as a reasonable strategy for success in the market. Specially in technical textile application cases, where the function as an objective criterion is primarily and essentially considered in decision-making, it may be more challenging for textile producers (seeking recyclable solutions) to substitute synthetic conventional types.

We have researched the answers to the 2 questions as research objective; (1) Can biosynthetic polymers fully replace fossil-based polymers in textile applications? and (2) What are the current challenges in establishing a fully circular business model in the textile industry? The findings of this review which is summarized as an answer to these 2 main questions focused on in this research are as following.

(1) Material solutions within polymer studies;

Polymers, as textile fiber materials that are primarily used in industry, have a wide range of applications owing to their functional properties. On the other hand, developing polymers that completely responds to functional needs and environmental concerns currently seems to be a target yet to be reached. New environmentally friendly polymerization and degrading agents/synthetic enzymes might be developed via biotechnological/synthetic biology solutions as well as nanotechnology and genetic engineering methods to be adapted for the production and degradation of polymers [18, 42, 43]. There are already nanotechnologic solutions developed to improve material properties for various applications via smart textile designs compatible with eco-design approaches [17].

(2) Circular business model within the scope of a polymer-based textile;

Circular economy principals should be considered when business models are formed, changed or transformed. The potential circular economy precautions and applications should be embedded to the business models based on companies own conditions and their determined business strategies [32, 34]. Specificly in textile industry polymer input is one of the material requires attention considering its technical advantages and environmental consequences.

Owing to varying abilities of polymer biodegradability depending on specific environmental/geographic conditions [40], countries may choose/develop specific polymer types that are environmentally better for their geography, considering geographic textile cluster [117] cooperation as well. Ecosystex member projects, such as herewear and regiogreentex, which are structured within the scope of Europe, and a high level of EU support for research and innovation on textile sustainability (euratex.eu) can serve as examples of locally developed solutions for sustainable textile production. Alternatively, or complementarily, they may incorporate an international circular business model across countries/regions within the scope of intrafirm or supplier−client cooperation. Supply chain and circular economy management can be positively influenced by a regionally paced textile production policy.

The eco-design approach should primarily be considered for minimizing negative environmental impacts and integrating environmental protection criteria throughout the life cycle of a product [72] with the context of eco-industrial ecology. Recycling technologies, on the other hand, have also generated new solutions via biologic and chemical base solutions, both of which are environmentally friendly [97]. When these technologies are adapted to close and open-loop recycling systems, the number of aggregated inert textiles can be significantly decreased. The technologies developed for eco-design products for certain applications and recycling operations have theoretically and experimentally proven themselves, although they are currently in the scaling stage of improvement. These technologies carry reasonable potential to be applied in textile operations to increasing extent when they complete their scaling stages to receive positive responses from the market as a consequence of improved environmental conditions, economic compatibility and quality features.

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Human and animal participants
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